9 Summary, Conclusions, and Recommendations for Future Research

The most important conclusions of this study can be summarized as follows:

9.1 Use and Interpretation of CSL Data

1. CSL data plots of velocity and energy are unreliable for detecting cracking and estimating concrete strength in drilled shafts.
2. CSL plots of velocity and energy are to some degree reliable for estimating concrete consistency.
3. CSL data processing techniques have potential to detect anomalies such as large voids and honeycomb regions.
4. Current methods employed for first arrival determination are arbitrary and open to manipulation.
5. Manipulation of arrival picks can result in velocity artifacts, or can eliminate existing defects.
6. Failure to account for variations in curing rates and shaft temperatures results in velocity artifacts.
7. Lack of tolerances in CSL data collection equipment results in velocity artifacts. This includes variations in source activation energy, source activation time, and receiver data acquisition trigger time.
8. Poor quality CSL data collection equipment results in poor quality, noisy, and unreliable data.
9. Tomography should not be used on CSL data that has not been carefully acquired. Tomography requires absolute data, not relative guidelines.

9.1.1 Effects of CSL Access Tubes

10. Failure to account for tube bending results in velocity artifacts. Access tube deviation surveys are critical.

11. PVC access tubes transmit higher amplitude signals than steel.
12. Steel access tubes are more resistant to breaking and bending during concrete placement and curing..
13. Steel access tubes reduce tube de-bonding due to lower thermal expansion. The thermal expansion of PVC is 5 times higher than steel.
14. Thermal expansion of access tubes results in tube de-bonding in the upper portions of the shaft.
15. Access tubes transport heat from the shaft. Resulting temperature gradients result in concrete cracking in the vicinity of the access tubes. This effect is often misinterpreted as tube de-bonding, as it also is more likely to occur in the upper portions of the shaft where tubes are exposed to the surface. Filling tubes with water prior to concrete placement reduces this effect.
16. Failure to account for sensor position and orientation in access tubes results in velocity artifacts.

9.1.2 The Potential of Numerical Modeling

17. Numerical modeling has potential to improve data processing for CSL and Sonic Echo. This includes in situ measurement of concrete properties, shaft evaluation outside of the reinforcement cage, shaft cohesion with the surrounding ground, shaft bulging or necking, and cracking defects.
18. Numerical modeling has potential to evaluate effects of shaft defects and estimate load capacity.
19. Numerical modeling has potential to account for variations in curing rates and estimate cracking extent.

9.1.3 Concrete Curing and Stress

20. Concrete cures as a result of chemical hydration processes, and does not dry by loss of moisture.
21. Surrounding ground conditions affect curing rates and temperature gradients. This includes lithology, ground water, and surface exposure.
22. Temperature gradients above a certain level result in cracking
23. Stress in the drilled shaft is not uniformly distributed through out the depth of the shaft.
24. Soil density, friction angles of geo-materials, defects in the shaft, and compaction levels are the major control factors for stress concentration.

9.2 Suggestions for Improvements

9.2.1 Use and Interpretation of CSL Data

1. Specify tolerances for more accurate CSL data acquisition.
2. Standardize signal processing and arrival picking techniques. Eliminate manual adjustments.
3. Collect signal in source tube to reduce errors introduced by data collection hardware.

9.2.2 Use of CSL Access Tubes

4. Fill access tubes with water immediately before concrete placement.
5. Require deviation surveys of access tubes
6. Use access tube material with a thermal expansion rate similar to concrete.

9.2.3 Concrete Pouring

7. Use mix with higher fly-ash content for larger shafts.

8. Reduce placement temperature of mix.
9. Insulate the top of the shaft and access tubes quickly after concrete placement.
10. Increase shaft monitoring. Instrument tubes and monitor shaft during concrete placement.

9.3 Suggestions for Future Direction65

1. Incorporate numerical modeling techniques for data processing, defect classification, and shaft capacity analysis.
2. Apply stress analysis with fracture and non-elastic constitutive modeling.